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Evaluating the Physical Layer Performance of an OFDM candidate for Fourth Generation Networks

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ABSTRACT

In this paper, work performed under the framework of the IST SATURN project for wide area cellular OFDM is presented in the context of 4G networks. The key link parameters for a 4G OFDM system are identified and physical layer performance results presented for a number of transmission modes and channel scenarios. Furthermore, the benefits of space-time block coding strategies are evaluated and multiple access techniques are discussed.

I. INTRODUCTION

Given the delay that occurs between the first consideration of a new standard and its eventual publication, it is neither unreasonable nor surprising that investigations have already begun into technology for a standard not expected to be released until 2010. A number of predictions for 4G systems have been published in the literature. For more detail in this area the reader is referred to [1-5]. Enhancements such as ad-hoc and self-organising networks, support of mobile IP, interworking with Digital Broadcasting infrastructure [6] and the use of 'software radio' technology have all been identified as likely features of a 4G network. The considerable spectral efficiency benefits offered by spatial-temporal coding techniques [7-9] and Multiple Input Multiple Output (MIMO) system architectures are also highly attractive for 4G systems. However, whilst all these technologies are highly likely to feature in a 4G standard, there remain many key unspecified issues and parameters - not least the operating frequency and transmission rate.

It is not the purpose of this paper to predict the future of cellular mobile communications or the specific nature of an anticipated 4G standard. Rather, this paper is intended to illustrate the potential benefits of the application of OFDM to such a standard.

Because of OFDM's capability to exploit wideband multipath conditions, it has rapidly established itself as the modulation scheme of choice for broadband wireless communications systems. Digital Terrestrial Television Broadcast (DTTB) standards specified the use of OFDM modulation in Europe (ETSI DVB-T [10]) and Japan (ARIB ISDB-T [27]). Similarly, Wireless Local Area Network (WLAN) standards, also specifying OFDM modulation, are currently being finalized in Europe (ETSI HIPERLAN/2 [11]), North America (IEEE 802.11a [12]) and Japan (ARIB HiSWANa [13]). OFDM was also one of the candidate transmission techniques for UMTS [14] and is now proposed for IEEE 802.16a [20,21] and ETSI BRAN HIPERMAN for broadband wireless access networks. The success of OFDM in recent wired and wireless broadband communications systems strongly suggests that it should be considered as a leading candidate for a future cellular communications standard, i.e. 4G.

This paper identifies and describes the key link parameters of OFDM for a potential 4G cellular standard. These include the number of carriers, the subchannel spacing, the choice of modulation scheme and channel coding, and the choice of the guard interval. The performance of the OFDM system for a number of transmission modes is presented and OFDMA and TDMA multiple access schemes discussed. Furthermore the benefits of a simple space time coded diversity technique [7-9] are evaluated.

II. CHANNEL SCENARIOS

In order to study the performance of 4G systems, it is essential that the transmission channels are satisfactorily characterised. The radio link performance in a mobile environment is primarily limited by Doppler and delay spread. In order to establish some assessment scenarios, the channels proposed in the Evaluation Report for ETSI UMTS Terrestrial Radio Access (UTRA) [14] are considered (Table 1). The channel is time varying, with Doppler rates, f_D, as high as 220 Hz when operating in the 2GHz band for vehicular channels. For the indoor and pedestrian channels, Doppler rates of ~5 Hz are expected.

Table 1: Rms delay spreads

Number	Test Environment	Rms (ns)
1	Indoor A	70
2	Indoor B	125
3	Outdoor to indoor and pedestrian A	65
4	Outdoor to indoor and pedestrian B	655
5	Vehicular A	370
6	Vehicular B	4000

III. OFDM FOR 4G

From Table 1 it can be seen that the channel models considered have a wide range of possible rms delay spreads. Tables 2 and 3 show possible values for the OFDM parameters and the transmission modes respectively.

Table 2: OFDM Parameters for 4G

Parameter	Value	Value
FFT Size	256	512
Operating Frequency	2GHz	2GHz
Bandwidth *(B)*	4096 kHz	4096 kHz
Useful Symbol Duration *(T)*	62.5 μs	125 μs
Guard Interval (T_g)	T_g=1/4 , 1/8	T_g=1/4 , 1/8, 1/16
Guard Interval Duration (T_g)	15.625μs *(T/4)*	31.25 *(T/4)*
Total Symbol Duration (T_{symbol})	78.125 μs (with GI =*T/4*)	156.25 μs (with GI =*T/4*)
Inner Channel Coding	Punctured 1/2 rate convolution code, K= 7, $\{133, 171\}_{octal}$	Punctured 1/2 rate convolution code, K= 7, $\{133, 171\}_{octal}$
Number of data sub-carriers (N_D)	216	432
Sub-carrier spacing (Δ_f)	16 kHz	8 kHz

Table 3: Mode dependent parameters

Mode	Modulation	Coding Rate, R	Nominal bit rate [Mbit/s]
1	BPSK	1/2	1.3824
2	QPSK	1/2	2.7648
3	QPSK	3/4	4.1472
4	16QAM	1/2	6.2206
5	16QAM	3/4	8.2944
6 (optional)	64QAM	3/4	12.4416

For this study an operating frequency of 2 GHz with a bandwidth of 4096 kHz is assumed. The individual carriers are modulated by either BPSK, QPSK, 16QAM, or 64QAM with coherent detection.

Channel coding can be performed on a service type basis. The following options could be available: (a) Convolutional coding, (b) Outer Reed Solomon (RS) + Outer interleaving + Convolutional coding, (c) Turbo coding.

Additionally, Automatic Repeat Request (ARQ) schemes can be employed for packet services with no delay constraints (for example, data services). High peak rate modes, such as mode 6 that have high PERs can be used in conjunction with ARQ protocols for non delay sensitive services. Interleaving will be used so that the channel coding performs well in the presence of burst errors, introduced by the fading channel. This paper considers the case of convolutional coding with soft decision Viterbi decoding.

The raw bit rate depends on the chosen modulation scheme. Channel coding also affects bandwidth efficiency. Different modes with different modulation and coding rates will provide a number of data rates. These modes can be selected by a link adaptation scheme. Table 3 shows the bit rate for the different transmission modes considered in this paper.

IV. PERFORMANCE RESULTS

Figure 1 presents the BER performance of the different transmission modes (for *N*=256) versus the average SNR for channel model 5 (Vehicular A - see Table 1). It is important to note that the symbol duration, *T*=78.125μs, is much smaller than the channel coherence time, even in case of fast variation (vehicular model), where the coherence time is approximately *Tc*≈3ms. Therefore, channel time variations can be neglected within each OFDM symbol.

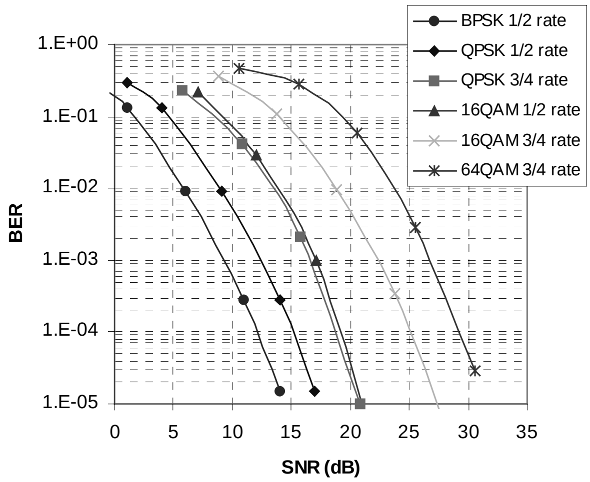

Figure 1: BER Performance of 4G system

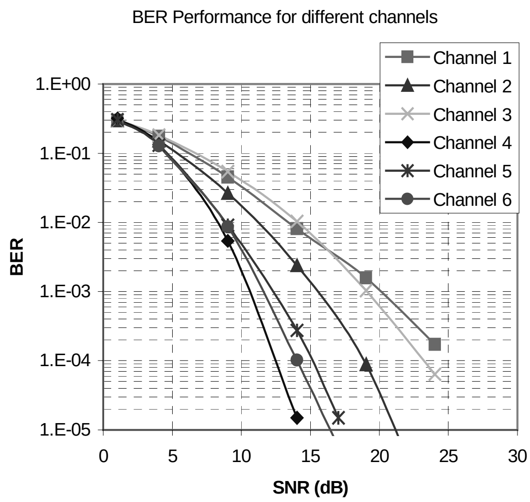

Figure 2: BER Performance for the different channels (QPSK 1/2 rate)

Figure 2 shows the simulated BER performance versus SNR for mode 2 under all considered channels. From Table 1 and Figure 2, it can be seen that as the delay spread increases the performance improves. This continues until the delay spread becomes so large that ISI and ICI become limiting factors (channel 6 for the case of *N*=256). For *N*=512, the performance in channel 6 will be better than channel 4. An FFT size of 512 can handle more ISI and can offer better GI efficiency.

However, it results in increased complexity of implementation and increased sensitivity to Doppler and phase noise.

V. SPACE TIME BLOCK CODING

In [7] Alamouti proposed a simple transmit diversity scheme which was generalized by Tarokh [16] to form the class of Space-Time Block Codes (STBC). These codes achieve the same diversity advantage as maximal ratio receive combining (allowing for a -3dB offset for the case of 2 Tx antennas due to power normalization) [9]. In [8], Lee and Williams applied a 2Tx-1Rx antenna, transmit diversity scheme to OFDM in order to achieve diversity gain over frequency selective fading channels. In this paper, STBC will be applied to an OFDM system with convolutional coding as described in the previous sections in order to enhance system performance.

In Alamouti's encoding scheme two signals are transmitted simultaneously from the two transmit antennas. The transmission matrix is given by [7-9,17]:

$$\mathrm{X}=\begin{bmatrix} X_1 & -X_2^* \\ X_2 & X_1^* \end{bmatrix} \tag{1}$$

where in the case of OFDM, X_1, X_2 are two consecutive vectors (forming a pair of vectors) to be input to the IDFT after the serial to parallel conversion (S/P) of the QAM modulated data [8]. At the first antenna, X_1 is transmitted during the first symbol period followed by $-X_2^*$ in the second symbol period. At the second antenna, X_2 is transmitted during the first symbol period followed by X_1^* in the second symbol period.

At receive antenna 1, after the DFT and the cyclic prefix removal, the received vectors are given by [7,8]:

$$\begin{aligned} Y_1 &= H_1X_1+H_2X_2+N_1 \\ Y_2 &= -H_1X_2^*+H_2X_1^*+N_1 \end{aligned} \tag{2}$$

where N_1, N_2 is AWGN and H_1 and H_2 are diagonal matrices whose diagonal elements are the frequency responses (DFT of h_1, h_2) of the channels between Tx1 and Rx1 and Tx2 and Rx1 respectively. It is assumed that the channel responses are uncorrelated and constant during the period of two OFDM symbols, something that is reasonable for the OFDM parameters chosen here, where T_{symbol} = 78.125μs.

After channel estimation, the channel parameters are known to the receiver, and the signals Y_1, Y_2 can be combined at the receiver according to [8,9]:

$$\begin{aligned} S_1 &= H_1^*Y_1+H_2Y_2^* \\ S_2 &= H_2^*Y_1-H_1Y_2^* \end{aligned} \tag{3}$$

Substituting for Y_1, Y_2 from (2), the combined signals can be written as [4,5]:

$$\begin{aligned} S_1 &= (|H_1|^2+|H_2|^2)X_1+H_1^*N_1+H_2N_2^* \\ S_2 &= (|H_1|^2+|H_2|^2)X_2+H_2^*N_1-H_1N_2^* \end{aligned} \tag{4}$$

In order to perform soft decision Viterbi decoding, the Channel State Information of both channels (H_1, H_2) is passed to the decoder in order to calculate the metric.

For the case of 1 Rx antenna, the above scheme is similar to that of two branch maximal ratio receive combining (MRRC). For the case of 2 Rx antennas, the signal from the two receivers are combined and the scheme performs similar to four branch MRRC. However, the Alamouti scheme has a 3 dB power loss compared to MRRC because each transmit antenna transmits half the power so that the average received power is the same when comparing receive diversity with transmit diversity [8,9].

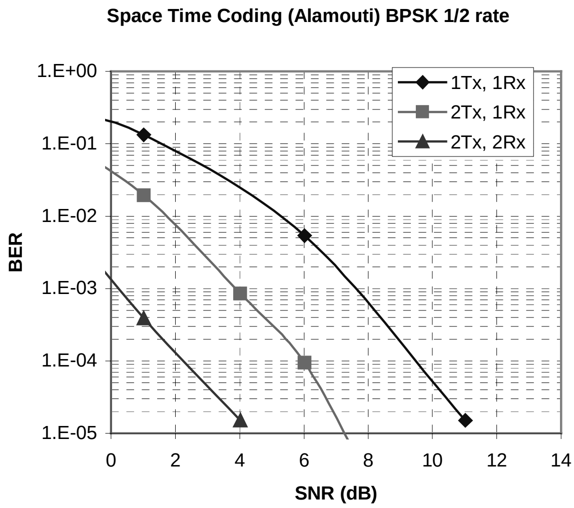

Figure 3: BER Performance with STBC

Figure 3 shows the BER performance of BPSK 1/2 rate versus SNR with STBC. It was assumed that a perfect channel estimate was available at the receiver. It can be observed that the performance is significantly improved for both the cases of 2Tx, 1Rx and 2Tx, 2Rx antennas. It can be seen that the proposed STBC provides ~3.8dB gain at a BER of 10^{-4} for the case of 2Tx and 1Rx antennas and a further 3.8dB gain for the case of 2Tx and 2Rx antennas.

VI. MULTIPLE ACCESS

This section is a review of possible multiple access schemes for OFDM. Because OFDM separates symbols in both time and frequency, it allows for a number of multiple access schemes. If we assume a TDMA approach, the base station informs the mobile stations at which point in time in a frame they are allowed to transmit their data. Time slots are allocated dynamically depending on the need for transmission resources. Multiple connections with different bit rates and QoS requirements can be established.

In general within a given time slot a mobile station may use all or some of the allocated subcarriers. Hence, the transmission rate of each mobile station may dynamically vary from slot to slot. This situation is known as orthogonal frequency division multiple access (OFDMA/TDMA or multi-user OFDM) [5,14,15,18-22,25]. Although this technique provides the means for extended flexibility and multirate transmission, it requires precise synchronisation between the mobile stations. However, OFDMA provides better coverage by allocating a power level that is a function of user distance on the downstream or by concentrating the available user terminal power on a few carriers in both the upstream and downstream. This additional power gain can be used to support a bigger cell radius, better coverage, better capacity or simpler power amplifiers, compared to a TDMA system. The OFDMA/TDMA scheme is capable of accommodating multirate traffic, which is essential to multimedia applications. It can also handle narrowband interference better than any other multiple access scheme, since the few bands that are corrupted can easily be discarded in the resource allocation process [25].

Using an OFDMA/TDMA system, subchannels are allocated in the frequency domain and OFDM symbols are allocated in the time domain. All usable carriers are divided into subchannels. For example, the 432 usable carriers (out of the 512) can be divided into 18 subchannels each containing 24 carriers.

The carriers of each subchannel can be either grouped or spread over the usable frequency band for best frequency diversity. Grouping carriers minimises inter-user interference but makes the transmission susceptible to fading. This can be overcome by frequency hopping the subcarriers [22]. Allowing hopping with different hopping patterns for each user can transform the OFDMA system in a frequency hopping CDMA system. This has the benefit of increased frequency diversity as well as interference averaging. In each group, two subcarriers at the edge of a band slot can be left unmodulated to relax receiver blocking requirements [14,15].

If the channel gains are known at the transmitter, (for instance, downlink transmission in a time division duplex system) an adaptive multiuser subcarrier allocation scheme can be applied [22,26]. After the channel has been characterised, each user is allocated subcarriers that have the best SNR for that user. Since each user will be in a different location, the subcarriers that are in deep fade for one user will not be in a deep fade for other users. However, this scheme is less useful at high velocities where the hopping cannot keep up with the rate of change of the channel [22].

In the proposal for the IEEE 802.16a standard for broadband wireless access networks [18,19] carriers are spread over the system bandwidth and are allocated by permutation of a basic series in order to achieve interference spreading and averaging. Some subcarriers can be used for time and power synchronisation and to decide on the user modulation and coding.

In the reverse link of an OFDMA system the signals from all users are combined in the channel and are received as a complete OFDM signal. Hence, all remote stations must be frequency and time synchronised in order for the transmitted signals to remain orthogonal to each other. Synchronisation algorithms for OFDMA systems have been proposed in [20,21]. In [20], a method that exploits the null subcarriers to enforce time and frequency synchronisation was proposed. In [21], an estimator that uses the redundancy in the received signal due to the use of cyclic prefix was proposed for OFDM systems where users are separated in subchannels with adjacent subcarriers. The estimates of the users' offsets are returned on a downlink control channel to the mobile stations which adapt their clocks and oscillators to the free-running reference clocks and oscillators at the base station [21].

In a TDMA system, enhanced performance is achieved by adapting the modulation and coding rate to the channel conditions and average traffic in the network. A TDMA scheme is employed in the HIPERLAN/2 WLAN standard [11].

Finally, in [24], OFDM was combined with spread spectrum code division multiple access to form multicarrier (MC)-CDMA. In [25], it was described that in a single cell, the maximum capacity will be the same for MC-CDMA and MC-TDMA and that their performance will be essentially the same at full load. Performance in MC-CDMA improves as the number of users is reduced, but the same type of improvement is also achievable in MC-TDMA by adapting the modulation and coding functions to the average traffic in the network [25].

VII. RANGE RESULTS

The path loss model for the vehicular environment in urban and suburban areas can be calculated using the propagation model shown below [23]:

$$L_P = 40(1 - 4x10^{-3}\Delta h_b)\log_{10} R - 18\log_{10}\Delta h_b + 21\log_{10} f + 80 \quad (5)$$

where R is the distance between the base station and mobile station (km), f is the carrier frequency (2000MHz) and Δh_b is the base station antenna height (m) measured from the average rooftop level. This model is valid for NLOS cases only and describes worse case propagation. Log-normal shadow fading with 10dB standard deviation is assumed in both urban and suburban areas [23]. In rural areas the path loss is lower than urban and suburban areas and a path loss closer to R^{-2} (LOS) may be more appropriate than R^{-4} [23].

If a maximum output power of 30dBm, a combined Tx and Rx antenna gain of 4dBi and a receiver threshold of -105dBm (NF=4dB) are assumed, the Max Path Loss (MPL) for reception is given by MPL = 30+4 -(-105) = 139 dB. Figure 4 shows the path loss for the vehicular environment based on equation (5).

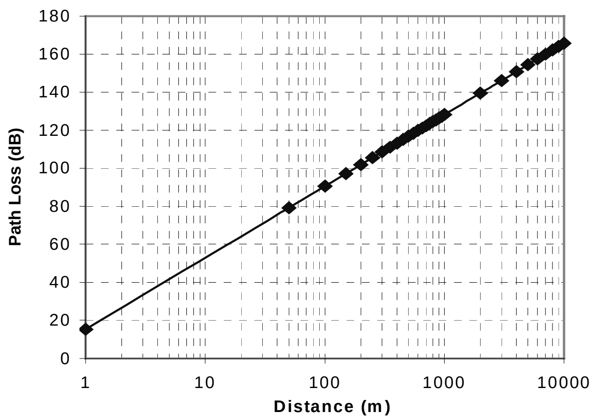

Figure 4: Path Loss for vehicular channels

From Figure 4, it can be seen that a cell radius of 2 km can be achieved under the conditions considered here. However, if the OFDMA system is employed an additional power gain can be achieved by concentrating the power into a few subcarriers. For example, the 432 usable carriers (out of the 512) can be divided to 18 subchannels each containing 24 carriers. A gain of $10\log_{10}(18)=12.5$dB is achieved for one subchannel allocation. Thus, the cell radius can be increased to 4.2 km (~2 times) for the NLOS scenario. For a LOS scenario a four fold increase is expected (from 10 km to 40 km).

VIII. CONCLUSIONS

In this paper, OFDM was proposed as a possible transmission technique for future 4G networks. The key link parameters were identified and initial performance results were presented for a number of channel models. The OFDM system supports adaptive modulation of BPSK, QPSK, 16QAM, and 64QAM and different coding rates and will provide data rates up to 12.5 Mb/s. If an OFDMA scheme is used for multiple access the bandwidth per user can be adapted, trading off distance and peak throughput per user. Hence, this system will be suitable for multimedia traffic, which is a key requirement for 4G systems. In order to achieve diversity gain and enhance performance, space-time block codes were employed. Although this scheme has low complexity and it is easy to implement, it provides considerable improvements in performance without any bandwidth expansion. A gain of ~7.5 dB was observed for BPSK 1/2 rate at a BER of 10^{-4} when 2 antennas were used in both the transmitter and receiver.

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